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Title Page***A novel Pah-exon1 deleted murine model of phenylalanine hydroxylase (PAH) deficiency***

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Abstract

Phenylalanine hydroxylase (PAH) deficiency, colloquially known as phenylketonuria (PKU), is among the most common inborn errors of metabolism and in the past decade has become a target for the development of novel therapeutics such as gene therapy. PAH deficient mouse models have been key to new treatment development, but all prior existing models natively express liver PAH polypeptide as inactive or partially active PAH monomers, which complicates the experimental assessment of protein expression following therapeutic gene, mRNA, protein, or cell transfer. The mutant PAH monomers are able to form hetero-tetramers with and inhibit the overall holoenzyme activity of wild type PAH monomers produced from a therapeutic vector. Preclinical therapeutic studies would benefit from a PKU model that completely lacks both PAH activity and protein expression in liver. In this study, we employed CRISPR/Cas9-mediated gene editing in fertilized mouse embryos to generate a novel mouse model that lacks exon 1 of the *Pah* gene. Mice that are homozygous for the *Pah* exon 1 deletion are viable, severely hyperphenylalaninemic, accurately replicate phenotypic features of untreated human classical PKU and lack any detectable liver PAH activity or protein. This model of classical PKU is ideal for further development of gene and cell biologics to treat PKU.

Keywords: Phenylketonuria; CRISPR/Cas9; Knockout Mouse Model; Gene Therapy

1. Introduction

Phenylketonuria (PKU) (OMIM # 261600) is among the most well-studied inborn errors of metabolism. PKU is most commonly caused by phenylalanine hydroxylase (PAH, EC 1.14.16.1) deficiency as the result of inherited *PAH* mutations, but can also be caused by mutations in the *DNAJC12* gene, one of the co-chaperones required for proper PAH folding and degradation [1]. PAH deficiency results in hyperphenylalaninemia (HPA) and irreversible neurological consequences if left untreated [2]. The PAH enzyme functions in liver as homo-tetramers to hydroxylate phenylalanine (Phe) into tyrosine and requires the co-factor tetrahydrobiopterin for catalysis [3]. Dietary phenylalanine (Phe) tolerance among PKU patients differs widely depending on the body's ability to maintain Phe homeostasis, resulting in a clinical continuum of phenotypes ranging from chronic mild hyperphenylalaninemia to severe classical PKU.

The *Pah^{enu2/enu2}* mouse model recapitulates classical PKU with toxic hyperphenylalaninemia that causes neurological damage if untreated, and due to this classical PKU phenotype, is the most utilized animal model for testing novel therapeutics. Elevated brain Phe impairs cognitive and behavioral performance, as well as proper monoamine neurotransmitter production [4]. Abundant stable, nonfunctional PAH protein that is recognized by anti-PAH antibodies is expressed in liver [5]. For research that aims to perform preclinical gene therapy studies, the presence of this mutant protein introduces confounding variables and challenges to experimental design, analysis, and interpretation. These challenges include the inability to distinguish transgene-derived functional enzyme from native mutant PAH by

immunohistochemistry, as well as the dominant negative effect of mutant monomers forming hetero-tetramers with functional monomers, thereby lowering the overall activity of the holoenzyme complex [6]. In order to better evaluate genetic therapeutic interventions, a model that is completely void of PAH protein and activity is greatly desired. To accomplish this task, this study sought to delete the entire first exon of the *Pah* gene in C57BL/6 mouse embryos using the CRISPR/Cas9 system [7].

2. Materials & Methods

2.1 Experimental Design

2.1.1 Guide Design and Validation

Single guide RNAs (sgRNA) were designed using the online guide design tools CHOPCHOP and MIT Guide Design, using nucleotides 87521818-87522107 of the murine GRCm38.p4 C57BL/6J chromosome 10 sequence, which contains the 5' untranslated region (5' UTR) through intervening sequence 1 (IVS 1) of the *Pah* locus. Of eight guides produced (Figure 1A), six were selected for further sgRNA investigation (guides 1,3,4,6,7,8). All guides were tested with the Takara Guide-It sgRNA *In-Vitro* Transcription Kit (Cat. No. 632635) and Screening System (Cat. No. 632639). Guides 3, 4, 6, 7 and 8 proved effective at inducing a targeted double-stranded break in the PCR substrate, and only guide 1 was unable to induce a cut in the target DNA (Figure 1B). The sgRNAs 4 and 8, located in the 5' UTR and IVS1, respectively, were selected for *Pah* gene targeting in murine embryos (Figure 1C).

2.1.2 Delivery of Cas9/sgRNA to mouse zygotes

Female C57BL/6N JAX® mice at 4-5 weeks of age were super-ovulated, mated with males, and 0.5 day old single cell zygotes were isolated as previously described [8]. Two approaches to accomplish mouse *Pah* exon 1 deletion were performed in this study. In the first approach, a mixture of Cas9 mRNA and sgRNAs were injected into the cytoplasm of the one-cell fertilized eggs [9]. In the second approach, electroporation of Cas9 protein/sgRNA (RNP) complex using the NEPA21 system (NEPA GENE Co. Ltd, Chiba Japan) was performed on single-cell fertilized eggs [10]. Zygotes from either

approach were then transferred into the oviducts of pseudo pregnant recipient CD1/NCrl foster dams (Charles River), and the surviving offspring were screened for sizable deletions in the *Pah* exon 1 region after weaning.

2.1.3 PCR Screen for Deleted Alleles

Tail biopsies were acquired from F0 animals at three weeks of age and screened for visually discernable deletions of 200 bp or more using standard PCR and gel electrophoresis. Forward primer 5'-GGTTGCGGAGAATCCATAC-3' and reverse primer 5'-TGACTAAGGACCAGCCATTTC-3' which are complementary to *Pah* sequences outside the putative Cas9 cleavage sites were used to amplify 753 bp spanning the 5' UTR and 3' IVS1 of exon 1 in the *Pah* locus using standard PCR with Invitrogen Platinum™ Taq DNA polymerase and the following cycling parameters: initial denaturation at 94°C for 5 minutes, followed with 30 cycles of denaturation at 94°C for 30 seconds, primer annealing at 55°C for 30 seconds, and extension at 72°C for 1 minute, and a final extension of 72°C for 5 minutes. Products were analyzed by electrophoresis on a 1% agarose gel with 1kb NEB ladder (Figure 1D and 1E). Bands approximately 500 bp in size were excised from the gel and purified with the Qiagen QIAQuick Gel Extraction kit (Cat. 28706X40) for Sanger sequencing.

2.1.4 Knockout-allele Sanger Sequencing

Purified approximately 500 bp PCR products described above were quantified using the Epoch Microplate Spectrophotometer and analyzed by standard Sanger sequencing with 5'-GGTTGCGGAGAATCCATAC-3' forward primer on an ABI 3130XL sequencer.

2.2 Animal studies

2.2.1 Animal husbandry

Animal care and experimentation were performed in accordance with the guidelines of the Dept. of Comparative Medicine, Oregon Health & Science University and the National Institutes of Health Guide for the Care and Use of Laboratory animals. The knockout *Pah* ^{Δ exon1/ Δ exon1} mice were produced through male *Pah*^{+/ Δ exon1} x female *Pah*^{+/ Δ exon1} as well as male *Pah* ^{Δ exon1/ Δ exon1} x female *Pah*^{+/ Δ exon1} crosses. Pups were toe clipped at two weeks for genotyping and identification purposes. All mice were fed tap water and standard mouse chow (LabDiet Picolab Rodent Diet 5LOD, St. Louis, MO) *ad libitum* providing approximately 24% protein and 1.04% L-phenylalanine by weight, except breeders that received high energy chow (LabDiet Rodent High Energy Diet 5058, St. Louis, MO) approximately 22% protein and 0.99% L-phenylalanine. Given that adult mice consume approximately 5 g chow per day, daily L-phenylalanine intake is estimated to be approximately 50 mg per day. The animals were housed under a standard 12 hours on, 12 hours off light cycle. All surgical procedures were carried out with inhaled isoflurane general anesthesia to minimize pain and discomfort.

2.2.2 Gene Therapy

Three 6-8 week old *Pah* ^{Δ exon1/ Δ exon1} mice (two males and one female) were treated with recombinant liver tropic adeno-associated virus serotype 8 vector containing AAV 2 genome (AAV2/8) that expressed the murine *Pah* cDNA from a strong Liver Specific Promoter (LSPmPAH) at doses of either 1×10^{10} vector genomes (vg) (1 male), 1×10^{11} vg (1 female), or 1×10^{12} vg (1 male) per mouse via retroorbital injection. An additional

control female animal was administered 1×10^{12} vg of a similar viral vector containing an inactivating frameshift mutation in the transgene, denoted as AAV2/8 LSPmPAHfs. Blood was obtained prior to AAV injection for measurement of blood Phe concentration. Two weeks later animals were harvested for molecular analyses, including serum and brain amino acid analysis, hepatic PAH enzyme activity, liver PAH fluorescent-immunohistochemistry, and quantitative PCR (qPCR) to determine vg copy number in total liver DNA.

A similar gene therapy study was performed in the *Pah^{enu2/enu2}* mouse model. Two cohorts of six adult *Pah^{enu2/enu2}* animals (3 male and 3 female) were administered 1×10^{11} vg or 1×10^{12} vg AAV2/8 LSPmPAH via retro-orbital injection. Blood was obtained prior to AAV injection for measurement of blood Phe concentration. Two weeks later animals were harvested for molecular analyses, including serum Phe concentration, hepatic PAH enzyme activity, and quantitative PCR (qPCR) to determine vg copy number in total liver DNA.

2.2.3 Euthanasia and tissue harvest

Animals were sedated using inhaled isoflurane anesthesia. Whole blood was collected by cardiac puncture, allowed to clot in an Eppendorf tube, and serum was separated by centrifugation. The mice were then euthanized by exsanguination and perfused with 20 mL normal saline via the left cardiac ventricle to clear blood from the liver and brain.

2.3 Molecular Characterization

2.3.1 Blood and Brain Amino Acids

Blood and brain amino acid concentrations were determined using an established protocol [4] by pre-column derivatization with 6-aminoquinolyl-N-hydroxysuccinimidyl carbamate (AQC, Waters AccQ Tag™ derivitization system) and separation by ultrahigh performance liquid chromatography and UV absorbance detection (Waters Acquity™ UPLC, Milford, MA) using the Waters Masstrak Amino Acid Analysis method (Figure 2B and 2C).

2.3.2 Brain Neurotransmitters

Mouse half brains were processed as previously described [4, 11] for the measurement of dopamine, homovanillic acid (HVA), 5-hydroxytryptophan (5-HTP), serotonin, and 5-hydroxyindoleacetic acid (5-HIAA) through ultrahigh performance liquid chromatography (UHPLC) and electrochemical detection basically as previously established [12].

Neurotransmitter concentrations were corrected for the total protein content of brain homogenate and reported as nmol/g protein (Figure 2D, 2E, 2F and 2G).

2.3.3 Liver PAH Enzyme Activity

PAH enzyme activity was determined in liver homogenates using a radiometric chromatography assay [13] with modifications [14], corrected for protein content, and normalized to the measured wild type C57Bl/6 liver PAH activity from the same run (Figure 3A).

2.3.4 Liver PAH Western Blot

Bulk liver homogenates were prepared by mechanical homogenization of four 10 mg biopsies in 800 μ L of cold lysis buffer, followed by centrifugation at 770 rpm for 8 minutes at 4°C. The supernatant was collected and quantified for protein concentration using the Micro BCA™ Protein Assay Kit from ThermoFisher (Cat. 23235). Each lane was loaded with a sample preparation containing 250 ng of protein in 1 μ L, NuPage LDS Sample Buffer, 50 mM dithiothreitol, and water up to a total volume of 10 μ L and incubated at 70° C for 10 min. 3 μ L of Magic Mark™ ladder and 10 μ L of each sample were loaded on a NuPage pre-cast gel and separated by electrophoresis in MOPS buffer at 200V for 50 minutes. The protein was transferred to a polyvinylidene fluoride membrane with electrophoresis in NuPage transfer buffer at 100V for 45 minutes. The membrane was blocked with 5% milk in TBS-T (Tris Buffer Saline-Tween) and probed with rabbit polyclonal anti-PAH antibody (1:200 dilution, BS3704 PAH (R400) from Bioworld, Inc.) and GAPDH loading control antibody (1:200 dilution, MA5-15738 GAPDH loading control antibody from Invitrogen) overnight. The membrane was washed with TBS-T and probed with HRP-conjugated goat anti-rabbit IgG secondary antibody (1:1000 dilution, A27034 Goat anti-rabbit IgG (H+L) from Thermo Scientific and m-IgG κ BP-HRP Sc 506102 from Santa Cruz Biotechnology) for one hour and washed. Bands were visualized using enhanced chemiluminescence (Chemiluminescent Western Blot Detection from ThermoScientific) captured on the Azure Sapphire Biomolecular Imager chemiluminescence detection system (Figure 3B).

2.3.5 Quantitative PCR for Vector Genome Copy Number in Total Liver DNA

Total liver genomic DNA from untreated *Pah* ^{Δ exon1/ Δ exon1} mice was spiked with linearized LSPmPAH vector DNA and then sequentially diluted to produce a series of qPCR standards with final concentrations of 0.1 vector genome/diploid liver genome (vg/dg), 1 vg/dg, 3 vg/dg, 10 vg/dg, 30 vg/dg, 100 vg/dg, or 300 vg/dg. Total liver DNA isolated from gene therapy treated animals (three AAV2/8 LSPmPAH animals and one AAV2/8 LSPmPAHfs animal), as well as an untreated *Pah* ^{Δ exon1/ Δ exon1} animal as a negative control, were subjected to qPCR, along with the standard series, using SYBR Select MM (Applied Biosystems), forward primer PAH7.125F, and reverse primer PAH10.12R, to produce fluorescently labeled PCR products. Amplification was carried out and analyzed on a Qiagen Rotor-Gene Q real-time thermocycler. The number of AAV vg/dg from gene therapy treated mice was then estimated by comparing the C_t values from the unknowns to a linear regression curve of C_t vs. vg/dg generated from the standard series (Table 1). Each standard sample was amplified in duplicate to generate the standard curve, while each unknown was amplified in triplicate with the mean vg/dg reported in Table 1.

2.3.6 Liver PAH Fluorescent Immunohistochemistry

Select animals of *Pah*^{+/+} and *Pah* ^{Δ exon1/ Δ exon1} genotype, as well as gene therapy treated *Pah* ^{Δ exon1/ Δ exon1} animals, underwent saline-paraformaldehyde perfusion in preparation for liver fixation and immunohistochemistry (Figure 3C and Figure 4). Under deep isoflurane inhaled anesthesia, mice were perfused with 0.9% saline via cardiac infusion

to clear the hepatic circulation of blood. Excised biopsies from each liver lobule were then fixed for 24 hours in fixation solution (4% paraformaldehyde in phosphate buffered saline) followed by immersion in 25% buffered sucrose for an additional 24 hours. Tissues were embedded in optimal cutting temperature media, sliced into 15 micrometer sections, and mounted on glass slides. Sections were treated (following blocking) with rabbit polyclonal anti-PAH antibody (1:200 dilution, BS3704 PAH (R400) from Bioworld, Inc.) and incubated for 2 hours at room temperature. After appropriate washes, sections were treated with Alexa 488-conjugated goat anti-rabbit IgG secondary antibody (1:150 dilution, A11008 Alexa Fluor 488 goat anti-rabbit IgG (H+L) from Invitrogen) and incubated for one hour at room temperature. After washing, cover slips were mounted with Vectashield mounting medium containing DAPI. Images were captured on a Nikon H550L fluorescence microscope.

2.3.7 PCR amplification and Sanger sequencing of potential CRISPR/Cas9 off target mutation sites

Possible sites of off-target sgRNA-Cas9 genotoxicity were selected for Sanger sequencing analysis using the *in silico* COSMID tool [15], which used the guide 4 and guide 8 target sequence to determine the top four off-target sites in the mouse reference genome (GRCm38) for each guide. Sanger sequencing was performed for each region with location, off-target sequence, COSMID score (where lower score indicates higher likelihood of sgRNA-Cas9 double strand break lesions) and Sanger sequencing chromatogram displayed in Supplemental Figure 1.

3. Results

3.1 Experimental Design

3.1.1 Guide Validation

Using two *in silico* single guide RNA (sgRNA) design tools, CHOPCHOP and MIT Guide Design, *Streptococcus pyogenes* Cas9 appropriate guides throughout the *Pah* 5' upstream untranslated region (5' UTR), exon 1, and intron 1 (IVS1) were identified (Figure 1A). Six sgRNAs (labeled guides 1, 3, 4, 6, 7 & 8) were selected to test for effective targeted double-stranded DNA breaks (DSB) (Figure 1A). Using the Takara *In Vitro* Guide-It assay, sgRNAs 3, 4, 6, 7 & 8 were identified as being effective at inducing a DSB in mouse DNA, provided the remaining necessary gene editing components, in an *in vitro* setting (Figure 1B). Guide 4 (5' UTR) and guide 8 (IVS 1) were selected to knockout exon 1 of the *Pah* gene in murine embryos (Figure 1C). After CRISPR/Cas9-mediated *Pah* gene targeting, the zygotes were transferred into oviducts of pseudo-pregnant females yielding eighty-five liveborn F0 progeny.

3.1.2 *Pah* exon1 Deletion Screen

DNA isolated from tail biopsies of 85 potentially genetically altered offspring were analyzed for large deletions. PCR amplification of a 753 bp fragment flanking exon 1 in the *Pah* locus was performed, followed by gel electrophoresis, and screening for the presence of visually discernable deletions spanning approximately 200 bp or more (Figure 1D). CRISPR-modified alleles that contained small indels not visually detectable or large deletions greater in span than the amplicon and that would therefore not be amplified with this screening procedure were not further sought. Apparent heterozygous

Pah exon 1 deletions were detected in four female pups using this screening procedure, but only two could be confirmed and analyzed upon Sanger sequencing. The first animal carried a 243 bp deletion that was designated as allele a (Figure 1C).

Unfortunately, this deleted allele was unable to be propagated through breeding and therefore was not further characterized. Fortunately, a 258 bp deletion spanning exon 1 in a second founder animal, confirmed with Sanger sequencing and designated as allele b, was successfully propagated to an F1 generation and bred to homozygosity (Figure 1C, 1D, 1E and 1F). Hereafter, we designate this mutant allele *Pah* ^{Δ exon1}, and mice that are homozygous for this deleted allele as *Pah* ^{Δ exon1/ Δ exon1}, heterozygous as *Pah*^{+/ Δ exon1}, and wild type as *Pah*^{+/+}.

3.2 Characterization of *Pah* ^{Δ exon1/ Δ exon1} animals

3.2.1 Breeding of C57BL/6-*Pah* ^{Δ exon1/ Δ exon1} Mice

Four *Pah*^{+/ Δ exon1} X *Pah*^{+/ Δ exon1} crosses generated 23 pups with the following genotypes obtained at two weeks of life: 6 *Pah*^{+/+}, 12 *Pah*^{+/ Δ exon1}, and 5 *Pah* ^{Δ exon1/ Δ exon1}. This yield of genotypes is consistent with the 1:2:1 ratio expected from Mendelian inheritance of a recessive trait (Chi square = 0.36, df=2, between the probability of 0.9 - 0.1, and thus the null hypothesis that there is no difference between the observed and expected ratios was not rejected). This result indicates that homozygosity for the *Pah* ^{Δ exon1} allele is not associated with embryonic or neonatal lethality. However, beyond 2 weeks age, we have observed spontaneous demise in 10/17 of *Pah* ^{Δ exon1/ Δ exon1} animals during the transition from nursing to dependence upon solid food. *Pah* ^{Δ exon1/ Δ exon1} mice that survive beyond weaning exhibit coat color hypopigmentation on an unrestricted diet (Figure 2A),

a characteristic phenotype of mouse models of PKU that results from phenylalanine-mediated competitive inhibition of the melanin-synthesizing enzyme tyrosinase [16].

3.2.2 Serum and brain amino acid profiles

Serum and brain amino acid profiles were examined in adult (6-12 week old)

Pah ^{Δ exon1/ Δ exon1} (N=6, 1 male and 5 female), *Pah*^{+/ Δ exon1} (N=3, 1 male and 2 female), and *Pah*^{+/+} (N=3, 1 male and 2 female) animals (Figure 2B). Serum phenylalanine levels in *Pah* ^{Δ exon1/ Δ exon1} mice averaged 2172 ± 275 μ M (mean \pm SD), consistent with severe PKU, and were significantly elevated in comparison to either *Pah*^{+/ Δ exon1} (80 ± 14 μ M) or *Pah*^{+/+} (78 ± 12 μ M) mice by one-way ANOVA (F (2,9)= 156.7, P < 0.0001). There was no difference of hyperphenylalaninemia between male and female *Pah* ^{Δ exon1/ Δ exon1} animals in an unpaired t-test, with an average of 2364 μ M in 3 male mice and 2248 μ M in 7 female mice (p-value 0.7035). Serum tyrosine concentration was statistically different between genotypes by one-way ANOVA (F (2, 9) = 6.090, P =0.0213) with *Pah* ^{Δ exon1/ Δ exon1} (49 ± 13 μ M) less than *Pah*^{+/+} animals (75 ± 10 μ M) but not significantly different from *Pah*^{+/ Δ exon1} (62 ± 5 μ M).

Brain homogenates were analyzed for Phe, as well as the amino acid neurotransmitter precursors for dopamine and serotonin, tyrosine and tryptophan, respectively (Figure 2C). Brain Phe content was statistically elevated in *Pah* ^{Δ exon1/ Δ exon1} mice (817 ± 90 nmol/g) in comparison to either *Pah*^{+/ Δ exon1} (146 ± 19 nmol/g) or *Pah*^{+/+} animals (114 ± 9 nmol/g) in a one-way ANOVA (F(2, 9) = 154.2, P < 0.0001). There were no statistical differences in brain tyrosine or tryptophan between the *Pah* ^{Δ exon1} allele genotypes

(Figure 2C), with brain Tyr of 90 ± 14 nmol/g and brain Trp of 26 ± 4 nmol/g in *Pah* ^{Δ exon1/ Δ exon1} animals. These data are similar to published brain large neutral amino acid profiles in *Pah*^{enu2/enu2} mice (brain Phe 762 ± 17 nmol/g, brain Tyr 85 ± 15 nmol/g, and brain Trp 20 ± 3 nmol/g) [4].

3.2.3 Brain Neurotransmitters

The content of the monoamine neurotransmitters dopamine, 5-hydroxytryptophan (5-HTP), serotonin, and their metabolites homovanillic acid (HVA) and 5-hydroxyindoleacetic acid (5-HIAA) were examined in adult *Pah* ^{Δ exon1} animals. There are two parallel pathways that lead to the synthesis and metabolism of dopamine and serotonin. In dopaminergic neurons, tyrosine hydroxylase converts tyrosine into L-DOPA, which can then be converted into dopamine by L-amino acid decarboxylase (L-AAAD). After dopamine is secreted into the synapse, it can either be taken up by dopamine specific transporter (DAT) or metabolized into HVA. In *Pah* ^{Δ exon1} animals, there was no difference in brain dopamine between *Pah* ^{Δ exon1/ Δ exon1} animals (196.8 ± 38.78 nmol/g protein), *Pah*^{+/ Δ exon1} animals (260.6 ± 102.4 nmol/g) and *Pah*^{+/+} animals (234.3 ± 24.13 nmol/g protein) by one-way ANOVA ($F(2,8) = 1.129$, $P = 0.3700$), (Figure 2D). Interestingly, there was a significant difference in brain HVA among the groups ($F(2,8) = 9.349$, $P = 0.0081$), but post hoc intergroup comparison revealed only an unexplained significant increase ($P = 0.016$) in brain HVA of *Pah*^{+/ Δ exon1} animals (28.51 ± 3.74 nmol/g protein) in comparison to *Pah*^{+/+} animals (19.04 ± 2.03 nmol/g) but no significant difference ($P = 0.9453$) between *Pah* ^{Δ exon1/ Δ exon1} animals (18.36 ± 3.73 nmol/g) and wild type mice (Figure 2E).

In the serotonergic neurons, tryptophan hydroxylase converts tryptophan into 5-HTP, which can then be converted by L-AAAD into serotonin. After serotonin is secreted into the synapse, it can either be taken up by serotonin reuptake transporters or metabolized into 5-HIAA. In contrast to dopamine, the brain serotonin content was significantly different among *Pah*^{+/+}, *Pah*^{+/ Δ exon1}, *Pah* ^{Δ exon1/ Δ exon1} mice (one-way ANOVA F (2,8) = 91.20, P < 0.0001), (Figure 2F). Brain serotonin content was significantly lower (p = 0.0001) in *Pah* ^{Δ exon1/ Δ exon1} animals (47.30 \pm 5.79 nmol/g protein) than in wild type animals (90.53 \pm 3.10 nmol/g). Inexplicably, brain serotonin was somewhat increased (P = 0.002) in *Pah*^{+/ Δ exon1} mice (122.1 \pm 12.8 nmol/g) although we analyzed only 3 mice in this group. Similarly, the brain content of 5-HIAA, a marker of serotonin turnover, was significantly different among the genotypes by one-way ANOVA (F (2, 8) = 22.42, P = 0.0005), (Figure 2G). Brain 5-HIAA was significantly decreased (P = 0.0048) in *Pah* ^{Δ exon1/ Δ exon1} animals (18.95 \pm 6.28 nmol/g protein) in comparison to *Pah*^{+/+} animals (73.60 \pm 10.11 nmol/ g protein). Brain 5-HIAA content was not significantly different (P = 0.1629) between wild type and *Pah*^{+/ Δ exon1} animals (100.3 \pm 32.24 nmol/g protein).

3.2.4 PAH Enzyme Activity

Liver PAH enzymatic activity was measured in homogenates from *Pah* ^{Δ exon1/ Δ exon1} and *Pah*^{+/ Δ exon1} mice and compared to that of the existing PKU model, *Pah*^{enu2/enu2} along with *Pah*^{+/ Δ exon1} mice (Figure 3A). Liver PAH enzyme activity is expressed as the percent of wild type C57BL/6 liver activity. As expected, PAH activity was undetectable in liver of either *Pah* ^{Δ exon1/ Δ exon1} or *Pah*^{enu2/enu2} mice. However, there was a surprising difference in the liver PAH activity measured in heterozygous *Pah*^{+/ Δ exon1} (58 \pm 7% wild type activity)

and *Pah*^{+/*enu2*} (29 ± 5% wild type activity) mice, with a $P < 0.0001$ via post-hoc intergroup comparison analysis with Tukey multiple comparisons test (Figure 3A).

3.2.5 PAH Protein Expression

Western blot analysis of bulk liver homogenate revealed no visible band for anti-PAH staining at the expected 50 kDa size in *Pah* ^{Δ *exon1*/ Δ *exon1*} animals (Figure 3B). There is a strong band for PAH in *Pah*^{+/+} animals, and less intense but visible PAH bands in *Pah*^{+/ Δ *exon1*} and *Pah*^{*enu2*/*enu2*} animals. Bands staining for GAPDH at 37 kDa reveal similar protein loading in all samples.

Liver fluorescent-immunohistochemistry using anti-PAH antibody conjugated to Alexa Fluor 488 (green) and nuclear staining with DAPI (blue), revealed strong PAH expression in *Pah*^{+/+} mice but complete absence of visible PAH expression in *Pah* ^{Δ *exon1*/ Δ *exon1*} animals (Figure 3C).

3.2.6 PCR amplification and Sanger sequencing of potential CRISPR/Cas9 off target mutation sites

PCR amplification and Sanger sequencing of the top four predicted off target sites for Cas9-mediated double strand breaks associated with each of the guide RNA sequences used to produce the *Pah* exon 1 deletion detected no deleterious sequence differences (Supplemental figure 1).

3.3 Gene Addition Therapy in *Pah* ^{Δ exon1/ Δ exon1} animals

3.3.1 Gene Therapy

In order to demonstrate applicability of this model, liver tropic recombinant adeno-associated virus serotype 8 (rAAV8) containing the murine *Pah* (*mPAH*) cDNA (rAAV2/8 LSPmPAH) [17] was administered to three homozygous *Pah* ^{Δ exon1} animals in a small preliminary dose escalation experiment. The highest, middle, and lowest doses (1×10^{12} vector genomes (vg), 1×10^{11} vg, and 1×10^{10} vg of rAAV2/8 LSPmPAH, respectively) were delivered systemically via retro-orbital injection. A control animal received rAAV2/8 vector containing a nonsense frameshift mutation that abolishes PAH expression (1×10^{12} vg rAAV2/8 LSPmPAHfs). The phenylalanine levels in the three treated animals showed substantial correction in blood (127 μ M, 194 μ M, and 235 μ M, respectively) and brain (382 nmol/g, 135 nmol/g, and 325 nmol/g, respectively) 14 days post-administration at all three vector doses while the animal that received the frameshift virus maintained elevated blood (1,928 μ M) and brain (1,222 nmol/g) Phe levels (Table 1). Interestingly, the gene therapy treated animals exhibited liver PAH enzyme activity (96.1%, 42.0%, and 4.8% of wild type C57BL/6 liver activity), rAAV2 vector genome copy number (49.7 ± 2.9 vg, 16.2 ± 3.1 vg, and 2.9 ± 0.2 vg/ diploid liver genome), and intensity of liver fluorescent-immunohistochemical PAH staining that correlated with the vector dose (Table 1 and Figure 4).

Similar gene addition therapy was administered to *Pah*^{*enu2/enu2*} animals (3 males and 3 females per dose) systemically through the retro-orbital route with doses of 1×10^{11} vg and 1×10^{12} vg of rAAV2/8 LSPmPAH, that conferred reduced Phe of 176 ± 52 μ M and

$99 \pm 22 \mu\text{M}$, respectively, % WT PAH enzyme activity of $7.7 \pm 2.2\%$ and $14.8 \pm 3.3\%$, respectively, and vg/dg of 8-42 vg/dg and 56-291 vg/dg, respectively (Table 1).

4. Discussion

This study was able to successfully generate a novel murine model for classical PKU completely void of hepatic PAH protein expression. *Pah*^{+/ Δ exon1} x *Pah*^{+/ Δ exon1} mating produced the expected 1:2:1 Mendelian ratios of *Pah*^{+/+} to *Pah*^{+/ Δ exon1} to *Pah* ^{Δ exon1/ Δ exon1} offspring. Additionally, female *Pah*^{+/ Δ exon1} x male *Pah* ^{Δ exon1/ Δ exon1} mating was productive, yielding progeny in a 1:1 ratio of *Pah*^{+/ Δ exon1} to *Pah* ^{Δ exon1/ Δ exon1} animals. Complete PAH deficiency did not cause embryonic or neonatal lethality. However, *Pah* ^{Δ exon1/ Δ exon1} mice struggled to wean from nursing to solid food more frequently than the prior existing *Pah*^{enu2/enu2} model, with increased mortality at weaning. They required more attention to husbandry at this period with delayed separation from their dam and provision of soft food placed directly in the bottom of the cage until they demonstrated consistent ability to reach the chow overhead in the cage lid. The precise reason for this difference in the phenotype at weaning between the *Pah* ^{Δ exon1/ Δ exon1} and *Pah*^{enu2/enu2} models requires further investigation. There were no other obvious differences in the physical phenotype or neurologic performance of the two models to explain the loss of *Pah* ^{Δ exon1/ Δ exon1} mice near weaning. Blood and brain amino acid concentrations including the levels of phenylalanine and tyrosine in adult mice that survived weaning did not differ significantly between the two mouse strains, with the exception that the effect of sex upon serum Phe seen in *Pah*^{enu2/enu2} mice (higher mean blood Phe in females than in males) was not demonstrated in *Pah* ^{Δ exon1/ Δ exon1} mice. Brain neurotransmitter evaluation in *Pah* ^{Δ exon1/ Δ exon1} mice revealed findings analogous to those previously reported in the *Pah*^{enu2/enu2} model, which showed minimal disruptions in the dopamine pathway, but significant deficiencies in serotonin production [4]. The main biochemical difference

between the *Pah* ^{Δ exon1/ Δ exon1} and *Pah*^{enu2/enu2} models is the complete lack of detectable PAH protein in the knockout mouse. Deleterious CRISPR/Cas9-mediated mutation at an off-target site is a theoretical, low probability event that could adversely affect the phenotype of *Pah* ^{Δ exon1/ Δ exon1} mice. PCR amplification and Sanger sequencing of the top four predicted off-target Cas9 cutting sites for each the two guides used to develop the mouse detected no genotoxicity at any of those eight locations, however this approach was not comprehensive for the entire genome. To eliminate the possibility of any adverse mutations at alleles other than *Pah*, we are currently outbreeding the *Pah* ^{Δ exon1} allele onto a clean C57BL/6 genetic background.

Prior to this, the available mammalian animal models of PKU consisted of mouse models denoted as *Pah*^{enu1/enu1}, *Pah*^{enu2/enu2}, and *Pah*^{enu3/enu3}, which were created by random N-ethyl-N-nitrosourea (ENU) mutagenesis [5]. The *Pah*^{enu3} allele, which is no longer available due to breeding difficulties and neonatal fatality, contained a frameshift mutation that caused premature termination of the tetramerization domain [18]. *Pah*^{enu1} and *Pah*^{enu2} alleles are missense mutations that result in phenotypes on opposite ends of the hyperphenylalaninemia spectrum and are the predominant models of PKU to date. An additional model of PKU combines *enu1* and *enu2* as a heteroallelic *Pah*^{enu1/enu2} model, recapitulating compound heterozygosity for *PAH* mutations which occurs in approximately 87% of humans with PKU [19, 20]. The *Pah*^{enu1/enu1} and *Pah*^{enu1/enu2} models are less desirable for gene and cell interventions due to their mild phenotype.

The longstanding and most popular mouse model for preclinical PKU gene therapy studies has been the *Pah^{enu2/enu2}* model, which is homozygous for a p.F263S (c.835 T>C) missense mutation in the central catalytic domain of PAH. It produces abundant albeit inactive PAH enzyme and recapitulates classical human PKU, with severe hyperphenylalaninemia, cognitive and behavioral disabilities, hypopigmentation, and occasional seizures. We and other groups have successfully treated adult *Pah^{enu2/enu2}* animals with AAV-mediated gene addition therapy demonstrating robust, long-term efficacy [17, 21-23]. Additionally, this model has been used in hepatocyte transplant studies [24-26] and CRISPR/Cas9-mediated gene correction of the *enu2* point mutation in neonatal [27] and adult animals [28]. While these studies have driven the advancements in PKU therapeutic development, there is a significant limitation in this model, specifically the expression of inactive PAH monomer, leading to barriers in both efficacy and molecular analyses of gene and cell therapeutic interventions. The expression of mutant PAH protein makes immuno-based molecular analyses using anti-PAH antibodies following gene therapy uninformative as the ability to quantify or localize transgene-delivered protein is limited. Additionally, it has been proposed that the native mutant PAH monomers interact with and reduce overall activity of wild type monomers, and in this mouse model, pose an additional barrier to efficacy in gene therapy studies.

The possibility that mutant PAH monomers might have a dominant negative effect upon the activity of wild type PAH was first suggested from a study of liver PAH activities measured in parents of children with PKU [29]. In these individuals who were presumably heterozygous for pathogenic *PAH* mutations (the study occurred prior to

cloning of the *PAH* gene), liver PAH activity measured only 4.4-23% of wild type activity rather than the 50% typically expected for a recessively-inherited disorder. In this new study, we now confirm significant differences in liver PAH enzyme activity between *Pah*^{+/Δexon1} and *Pah*^{+/enu2} heterozygous animals, indicating that the production of mutant F263S monomers in *Pah*^{+/enu2} heterozygous mice adversely impacted the proper function of wild type PAH. These data provide strong *in vivo* evidence for the dominant negative effect of at least this single missense *Pah* mutation. Further studies are warranted to confirm these findings and extend them to the *Pah*^{enu1} model. We propose that this phenomenon may extend to multiple human missense *PAH* mutations.

Preliminary results from a small liver-directed AAV8-mediated dose escalation gene addition trial in three *Pah*^{Δexon1/Δexon1} mice revealed the utility of this model for liver gene transfer studies particularly in regard to employing anti-PAH immunohistochemistry in the assessment of hepatocyte transduction frequency, a feat that was previously unachievable in existing murine models. Furthermore, comparison of the efficacy in this small trial to the efficacy of *Pah*^{enu2/enu2} mice corroborates the suspicion that F263S mutant monomers present in the latter model inhibit the activity of wild type transgene-produced PAH and thereby limit treatment efficacy. Despite similar vector genome numbers within hepatocytes of the *Pah*^{Δexon1/Δexon1} and *Pah*^{enu2/enu2} animals, PAH enzyme activity was far greater in the *Pah*^{Δexon1/Δexon1} animals (Figure 3A). More *Pah*^{Δexon1/Δexon1} animals need to be treated to confirm these findings, but nevertheless we are confident in reporting that this knockout model is more sensitive to therapeutic intervention and is better able to depict a more accurate analysis of vector genome to

PAH activity due to the lack of mutant monomer expression, ameliorating the dominant negative effect observed in *Pah^{enu2/enu2}* mice.

In conclusion, we report the development of a novel PAH deficient murine model harboring a recessively inherited deletion of *Pah* exon 1. Because anti-PAH immunohistochemistry can be readily employed to track hepatocyte transduction following gene therapy, in addition to an apparently improved therapeutic threshold in comparison to the existing *Pah^{enu2}* model, we predict that this novel model will find particular utility in the future investigation of gene addition and gene editing methods. Importantly, with AAV-mediated gene addition therapy for PKU now entering human trials, this model provides a platform to more clearly correlate gene therapy treatment with physiological outcomes and aid our understanding of clinical trial results. While creating a model for classical PKU gene therapy with fewer confounding variables and enhanced molecular analyses was the impetus for this project, the overarching goal of generating this model was to add to the experimental tools available for PKU scientists and to advance PKU research.

Figure Legends

Figure 1: Experimental Design, Screening, and Sequencing.

A. *In silico* Guide Generation. The table displays the six guides that were selected for *in vitro* analysis using the MIT Guide Design *in silico* tool. Guide ID, Target Sequence, PAM site, Strand (plus or minus), and MIT Score are displayed, where higher scores indicate an improved prediction for cutting efficiency. **B. *In vitro* Guide Validation.** Gel electrophoresis of *in vitro* Guide-It Takara Assay performed with the six guides identified in Supplemental 1A and run on a 3% agarose gel. In the left gel, Guide1 displays no cutting of substrate, while guides 7 and 8 display partial cutting of substrate into 300 bp and 500 bp bands and 200 bp and 600 bp bands, respectively. In the right gel, Guides 3, 4, and 6 show complete cutting of substrate, with a doublet of 400 bp bands from guide 3 cutting, 300 bp and 500 bp from guide 4, and 350 bp and 450 bp from guide 6. Of note, guide 1, the only guide that did not demonstrate substrate cutting. **C. *Pah* exon 1 knockout design.** The diagram illustrates the experimental design to use CRISPR/Cas9 mediated technology with strategically selected sgRNAs to knockout exon 1 of the *Pah* locus. The gene structure of murine *Pah*, located on chromosome 10, is shown with exon 1, exon 2, exon 12, and exon 13 labeled, and // indicates the gene structure containing exons 3-11. Locations of Guide 4 (5' UTR) and Guide 8 (exon1-IVS1 junction) are displayed and placed below the *Pah* structure due to targeting of the minus strand DNA sequence. The PCR design to detect large, 200+ bp deletions in the 5' *Pah* locus is indicated with black arrows to represent primers. Forward primer is located in the 5' UTR and 3' primer is located in IVS1 (where // indicates DNA gap), resulting in amplification a 753 bp product that flanks exon 1 in the absence of gene

modification. Two founder females were identified with deletions spanning exon 1; one animal contained a deletion of 243 bp, designated allele a, and the other animal contained a deletion of 258 bp, designated allele b. **D. Gel electrophoresis of F0**

***Pah*^{+/ Δ exon1} female mouse.** Tail biopsy DNA from potential *Pah*^{+/ Δ exon1} founder mice was amplified with the primers described in Figure 1C. All mice have expected the expected wild type ~750 bp band but founder b (693) carries an additional ~500 bp band representing an allele with a ~250 bp deletion. **E. Gel electrophoresis of F2 *Pah* ^{Δ exon1}**

allele progeny. Genotyping of the progeny from a *Pah*^{+/ Δ exon1} X *Pah*^{+/ Δ exon1} breeding:

Mouse 37 (*Pah*^{+/ Δ exon1}), Mouse 38 (*Pah* ^{Δ exon1/ Δ exon1}), Mouse 39 (*Pah*^{+/+}), Mouse 40

(*Pah* ^{Δ exon1/ Δ exon1}), Mouse 41 (*Pah*^{+/ Δ exon1}), and Mouse 42 (*Pah*^{+/ Δ exon1}). *Pah*^{+/+} contains a

single ~750 band, *Pah*^{+/ Δ exon1} contains two bands, a ~750 bp band and a ~500 bp band,

and *Pah* ^{Δ exon1/ Δ exon1} contains a single ~500 bp band. **E. Sanger Sequencing of**

***Pah* ^{Δ exon1} Allele.** The chromatogram displays 12 nucleotides spanning in either direction from the deleted region in the *Pah* ^{Δ exon1} allele, indicated with the black triangle.

Figure 2: Characterization Amino Acids & Derivatives in *Pah* ^{Δ exon1} Mice

A. Coat Pigmentation. Photograph of untreated *Pah* ^{Δ exon1/ Δ exon1} (left) and *Pah*^{+/ Δ exon1}

(right) mice on standard mouse chow diet. **B. Serum Phe & Tyr.** Mean serum

phenylalanine and tyrosine concentration (\pm SD) of adult *Pah* ^{Δ exon1/ Δ exon1}, *Pah*^{+/ Δ exon1}, and

Pah^{+/+} animals following euthanasia. The left y-axis indicates μ M serum amino acid

concentration. The average serum Phe was 2172 μ M, 80 μ M, and 78 μ M, respectively.

One-way ANOVA revealed significant effects of genotype on serum Phe (F (2,9)=

156.7, P < 0.0001). The average serum Tyr was 49 μ M, 62 μ M, and 75 μ M,

respectively. One-way ANOVA revealed significant effects of genotype on serum Tyr between *Pah* ^{Δ exon1/ Δ exon1} and *Pah*^{+/+} animals ($F(2, 9) = 6.090$, $P = 0.0213$).

C. Brain LNAAs. Mean brain LNAA concentrations (\pm SD) of *Pah* ^{Δ exon1/ Δ exon1}, *Pah*^{+/ Δ exon1}, and *Pah*^{+/+} animals at time of euthanasia. The y-axis indicates amino acid concentration in nmol/g wet weight. The average brain Phe was 817 nmol/g, 146 nmol/g, and 114 nmol/g, respectively. One-way ANOVA revealed significant effects of genotype on brain Phe ($F(2, 9) = 154.2$, $P < 0.0001$). The average brain Tyr was 90 nmol/g, 105 nmol/g, and 100 nmol/g, respectively and brain Trp was 26 nmol/g, 32 nmol/g, 28 nmol/g, respectively. One-way ANOVA revealed no statistical differences in brain Tyr or Trp in *Pah* ^{Δ exon1} allele mice.

D. Brain Dopamine. Brain dopamine concentrations in nmol/g protein (y-axis) of individual animals (represented as single points) in each genotype of *Pah* ^{Δ exon1} allele mice (x-axis). There was no statistical significance in brain dopamine across genotypes by one-way ANOVA ($F(2,8) = 1.129$, $P = 0.3700$).

E. Brain HVA. Brain HVA concentrations in nmol/g protein (y-axis) of individual animals (represented as single points) in each genotype of *Pah* ^{Δ exon1} allele mice (x-axis). There was a significant difference in brain HVA across genotypes (one-way ANOVA $F = [2, 8] = 9.349$, $p = 0.0081$) with post-hoc multiple comparisons showing a significant increase of HVA in heterozygous animals in comparison to WT animals (adjusted $P = 0.016$) but no difference between homozygous and WT animals (adjusted $P = 0.9453$).

F. Brain Serotonin in *Pah* ^{Δ exon1} Allele Mice. Brain serotonin concentrations in nmol/g protein (y-axis) of individual animals (represented as single points) in each genotype of *Pah* ^{Δ exon1} allele mice (x-axis). There was a significant difference in brain serotonin across genotypes (one-way ANOVA ($F[2,8] = 91.20$, $P < 0.0001$), with significantly less brain

serotonin in *Pah* ^{Δ exon1/ Δ exon1} animals (47.30 nmol/g protein) than wild type (90.53 nmol/g protein) or heterozygous (122.1 nmol/g protein) animals. **G. Brain 5-HIAA.** Brain 5-HIAA concentrations in nmol/g protein (y-axis) of individual animals (represented as single points) in each genotype of *Pah* ^{Δ exon1} allele mice (x-axis). There was a significant difference in brain 5-HIAA across genotypes (one-way ANOVA: F [2,8] = 22.42, p = 0.0005), with less brain 5-HIAA in *Pah* ^{Δ exon1/ Δ exon1} animals (18.95 nmol/g protein) than wild type (73.6 nmol/g protein) or heterozygous (100.3 nmol/g protein) animals.

Figure 3: Characterization of PAH in *Pah* ^{Δ exon1} Mice

A. Liver PAH Enzyme Activity. Mean liver PAH enzyme activity (\pm SD) in homozygous and heterozygous *Pah* ^{Δ exon1} and *Pah*^{enu2} mice. The y-axis indicates liver PAH activity expressed as percent wild type (WT) PAH enzyme activity. The average enzyme activity was 58% in *Pah*^{+/ Δ exon1} and 29% in *Pah*^{+/ Δ enu2}, while all homozygous recessive animals were 0%. One-way ANOVA revealed statistical differences in percent WT PAH enzyme activity across these genotypes (F (3, 18) = 212.7, P < 0.0001). **B. Liver PAH Western Blot.** Western blot analysis of anti-PAH and anti-GAPDH in liver homogenates from *Pah* ^{Δ exon1} allele and *Pah*^{enu2/enu2} mice. The arrows on the left of the image indicate band sizes for PAH at 50kDa (top) and GAPDH at 37kDa (bottom). **C. Liver PAH Fluorescent Immunohistochemistry.** Anti-PAH fluorescent immunohistochemistry in liver tissue samples from *Pah*^{+/+} and *Pah* ^{Δ exon1/ Δ exon1} mice. Green indicates the presence of PAH by anti-PAH antibodies bound by secondary antibodies conjugated with AlexaFluor 488 (green fluorescence) and blue indicates nuclear staining with DAPI. The left image depicts PAH IHC on untreated *Pah*^{+/+} liver tissue with strong green signal and

top right image displays PAH IHC of untreated *Pah* ^{Δ exon1/ Δ exon1} liver tissue with absent green signal.

Table 1: Molecular Analyses of Gene Therapy Treated *Pah* ^{Δ exon1/ Δ exon1} and *Pah*^{enu2/enu2} Mice. Pre- and post- gene therapy (GT) effects in a dose escalation experiment in *Pah* ^{Δ exon1/ Δ exon1} mice, as well as gene addition therapy in *Pah*^{enu2/enu2} animals. The first column indicates the gene therapy administered, including dose and transgene, where rAAV2/8 LSPmPAH indicates a therapeutic virus containing an rAAV2 genome with a transgene cassette containing a Liver Specific Promoter driving murine PAH packaged into an AAV8 capsid. The AAV2/8 LSPmPAHfs contains a frameshift and is used as a control vector.

Figure 4: Liver PAH Fluorescent Immunohistochemistry of Gene Therapy Treated *Pah* ^{Δ exon1/ Δ exon1} Mice. Anti-PAH fluorescent-immunohistochemistry in liver tissue samples from gene addition therapy treated *Pah* ^{Δ exon1/ Δ exon1} mice. Green indicates the presence of PAH by anti-PAH antibodies bound by secondary antibodies conjugated with AlexaFluor 488 (green fluorescence) and blue indicates nuclear staining with DAPI. The four images display the gene therapy treated *Pah* ^{Δ exon1/ Δ exon1} mice as labelled according to dosing of therapeutic vectors of LSPmPAH AAV2/8: 1 X 10¹² vg (top left image labelled with **1E12**), 1 X 10¹¹ vg (top right image labelled with **1E11**), and 1 X 10¹⁰ vg (bottom left image labelled with **1E10**), followed by 1 X 10¹² vg of the control vector (LSPmPAHfs) containing a frameshift (bottom right image labelled with **1e12fs**).

Supplemental Figure 1: sgRNA Off-Target Sanger Sequencing

A. Guide 4 Off-Target Sanger Sequencing. Guide 4 sequence with PAM site is displayed at the top, followed by chromatograms displaying the top four Guide 4 off-target sites, including location, sequence (PAM site in red), and COSMID score. **B.**

Guide 8 Off-Target Sanger Sequencing. Guide 8 sequence (with PAM site in red) is displayed at the top, followed by chromatograms displaying the top four Guide 8 off-target sites, including location, sequence (PAM site in red), and COSMID score.

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Author Contributions

D.R. performed the experiments, analyzed data, and wrote the manuscript.

L.F. assisted with experimental design and manuscript editing.

S.W. performed surgical procedures and assisted with experimental design, mouse breeding, molecular techniques, and editing of the manuscript.

S.D. assisted with mouse breeding and molecular techniques.

N.R. and B.T. performed the brain monoamine neurotransmitter analysis, and B.T. edited the manuscript.

C.H. assisted with funding, experimental design, analyses, data interpretation, manuscript editing, and was primary mentor to D.R. during graduate school.

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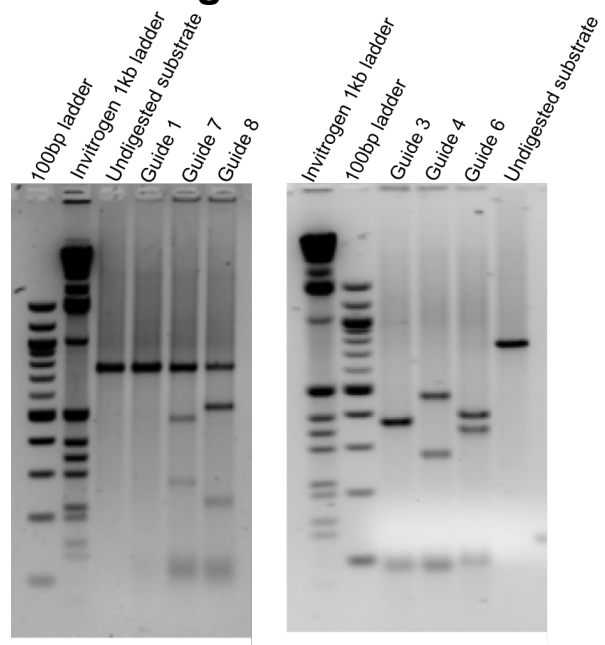
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Figure
Richards et al. Figure 1: Experimental Design, Screening, and Sequencing

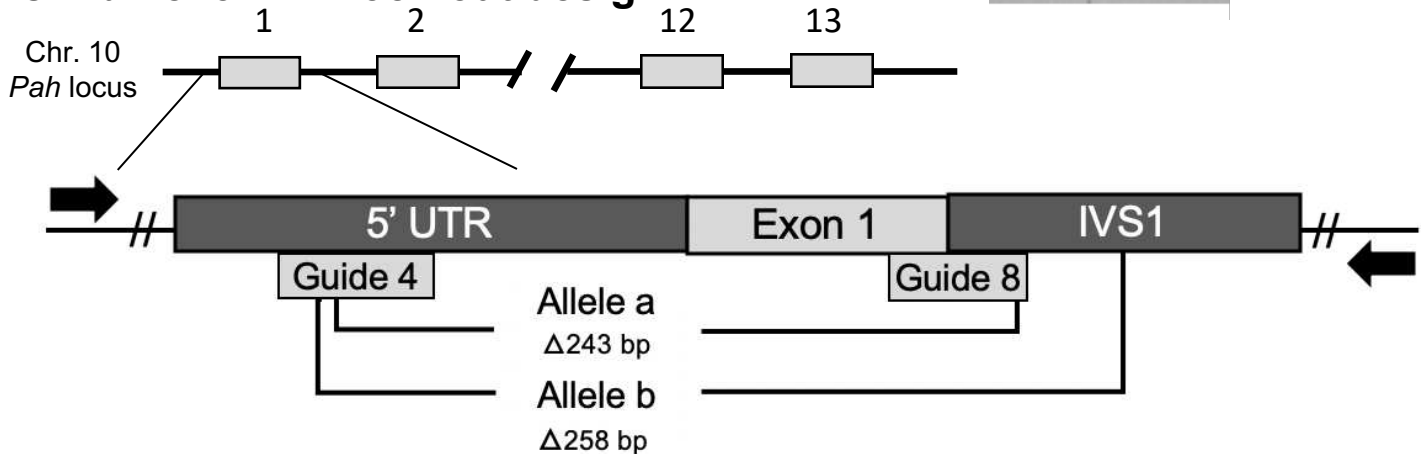
A. *In silico* guide generation

Guide ID	Target Sequence	PAM	Strand	MIT Score
Guide 1	TGTCTATCCACTGCTACGTC	AGG	Plus	90
Guide 3	CGGGGCTGATGGTTTAAACC	TGG	Minus	87
Guide 4	GTGTTGCCCTGACGTAGCAG	TGG	Minus	84
Guide 6	GTTAGGAAAAGTTTGCACTC	AGG	Minus	75
Guide 7	TGCTCAGGACTCCGTTCTCC	AGG	Minus	74
Guide 8	TTTGGGCAGGTAAGCCTGTT	GGG	Plus	73

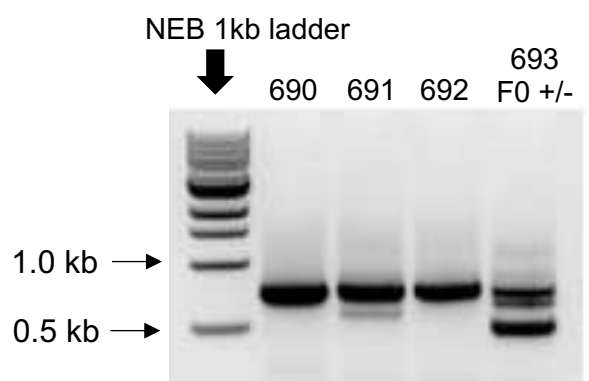
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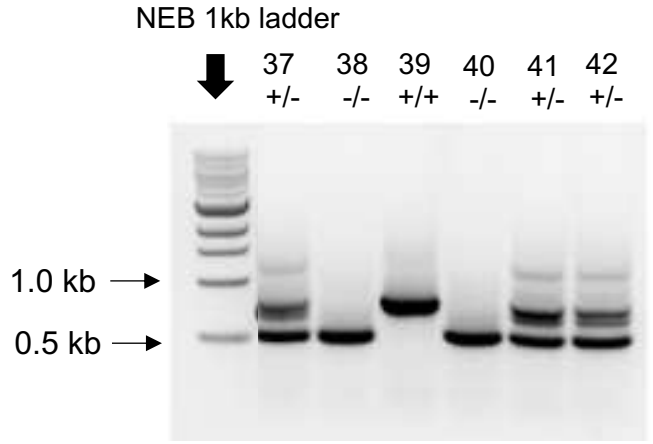
C. *Pah* exon 1 knock-out design



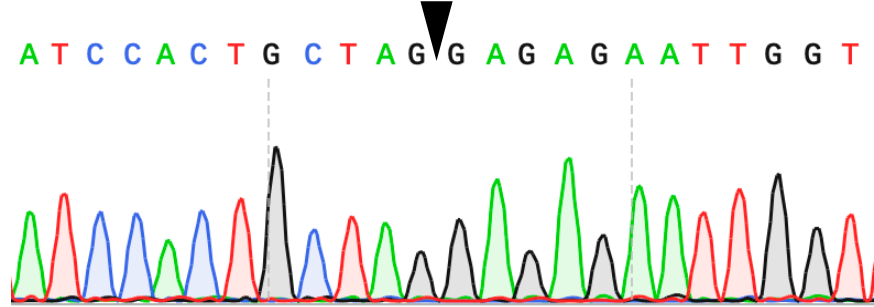
D. Gel electrophoresis of F0 *Pah*^{+/-Δexon1}



E. Gel electrophoresis of F2 litter



F. *Pah*^{Δexon1} Sanger Sequencing



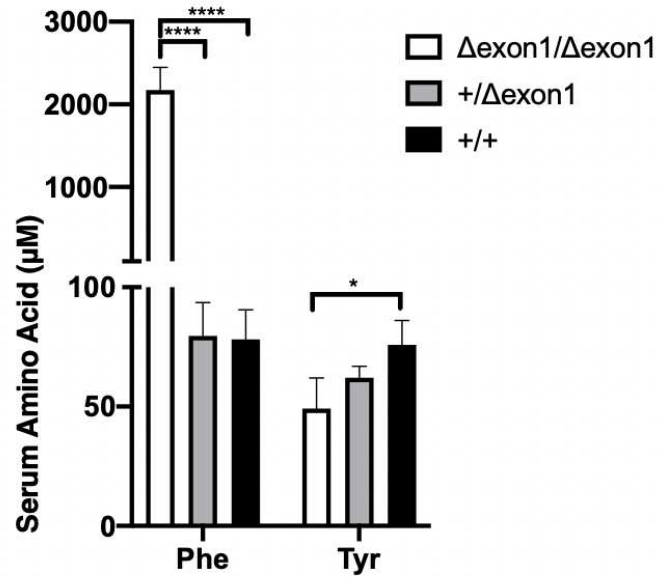
Richards et al. Figure 2: Characterization Amino Acids & Derivatives in *Pah* ^{Δ exon1} Mice

A. Coat Pigmentation

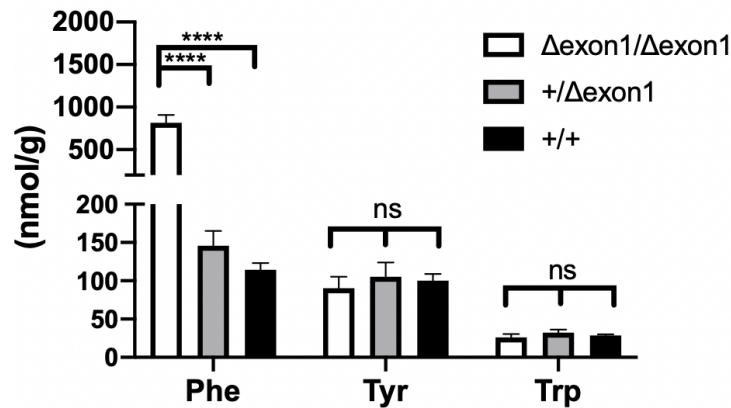


Pah ^{Δ exon1}/*Δexon1* *Pah*⁺/*Δexon1*

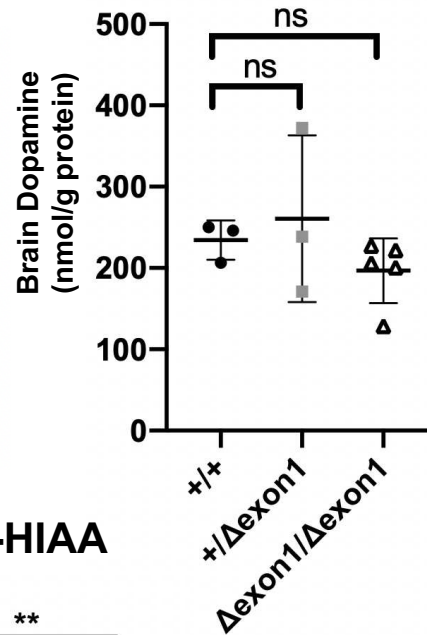
B. Serum Phe & Tyr



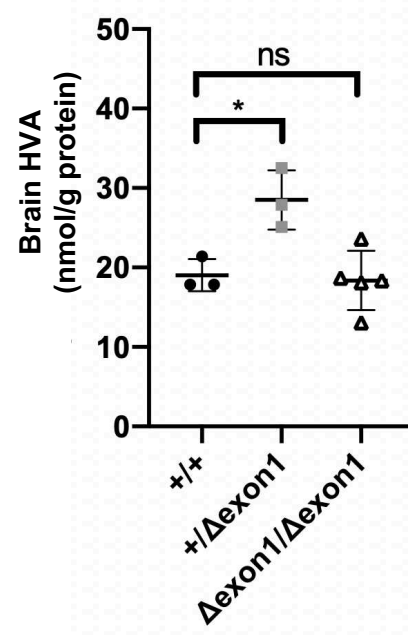
C. Brain LNAAs



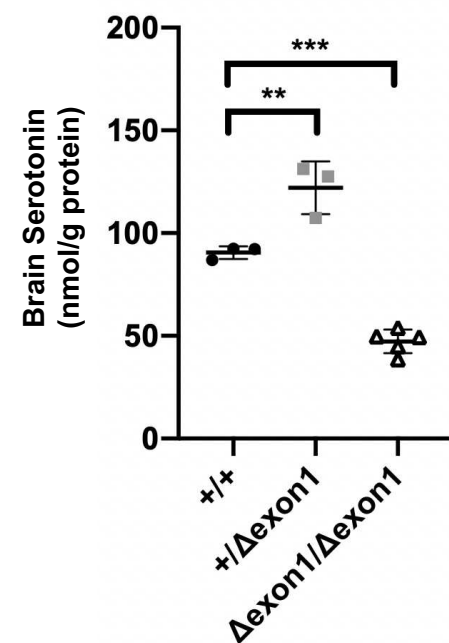
D. Brain Dopamine



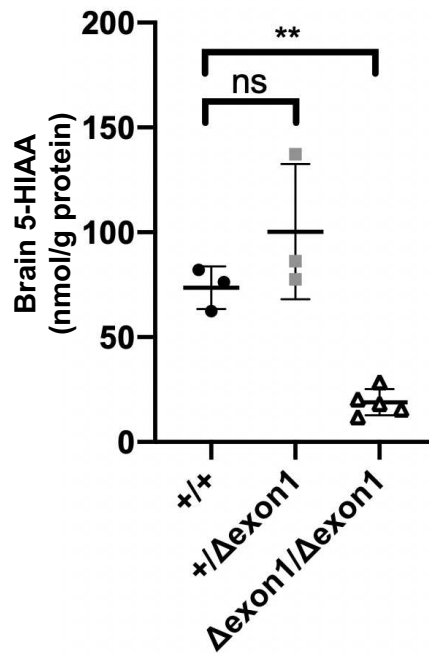
E. Brain HVA



F. Brain Serotonin

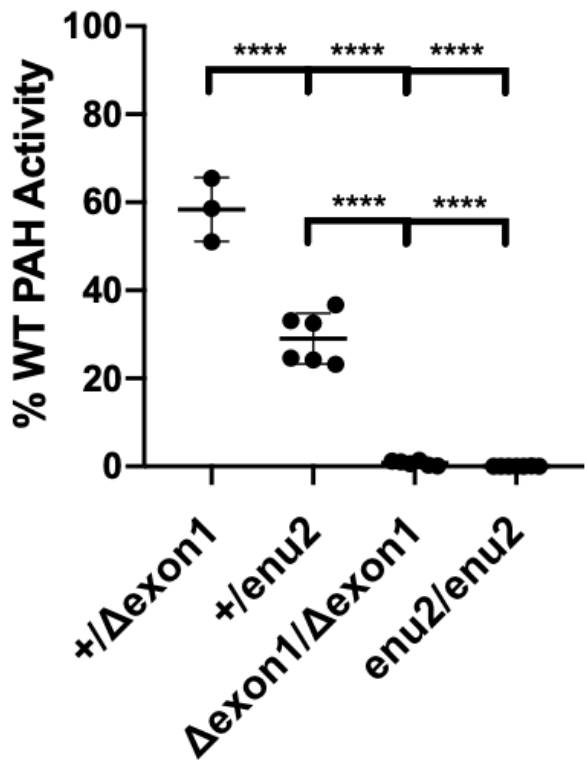


G. Brain 5-HIAA

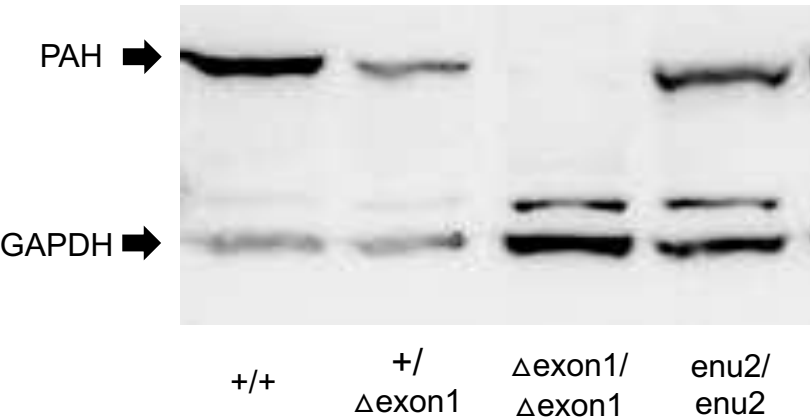


Richards et al. Figure 3: Characterization of PAH in *Pah* ^{Δ exon1} Mice

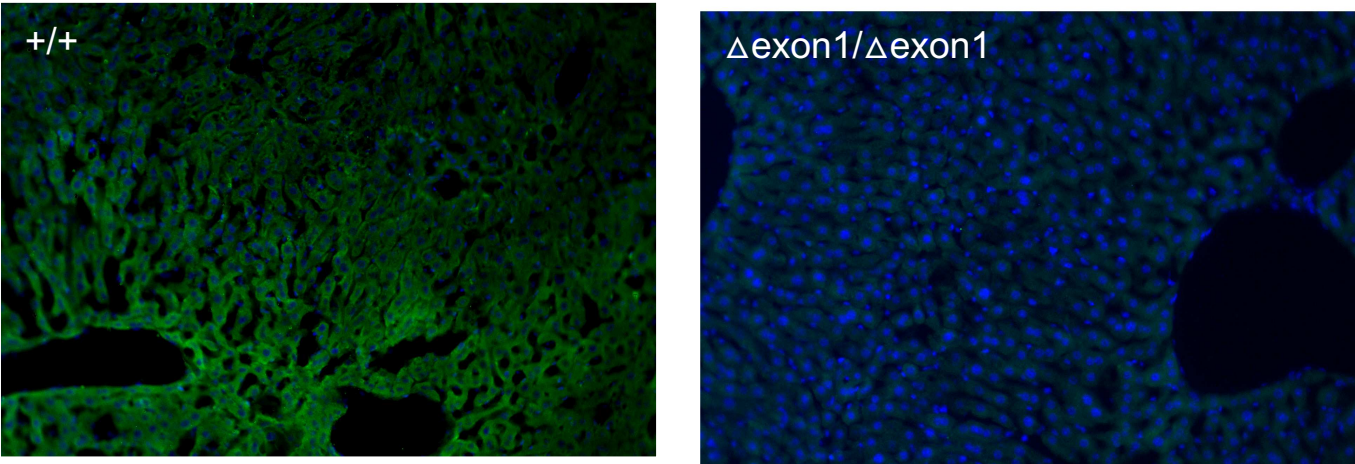
A. Liver PAH Enzyme Activity



B. Liver PAH Western Blot



C. Liver PAH Fluorescent Immunohistochemistry

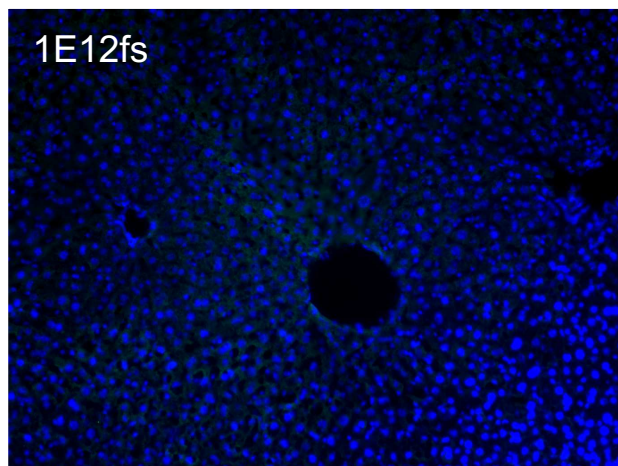
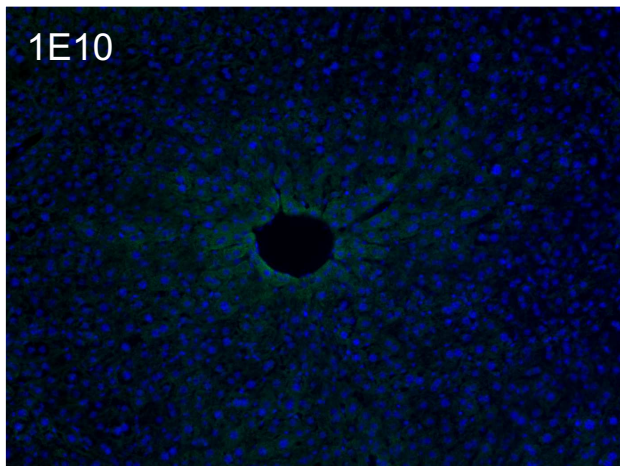
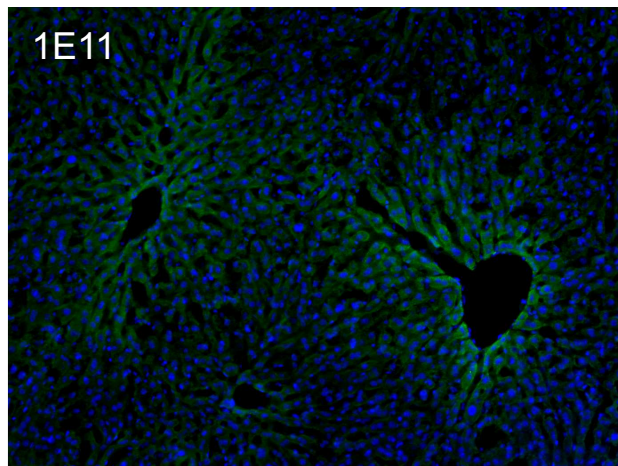
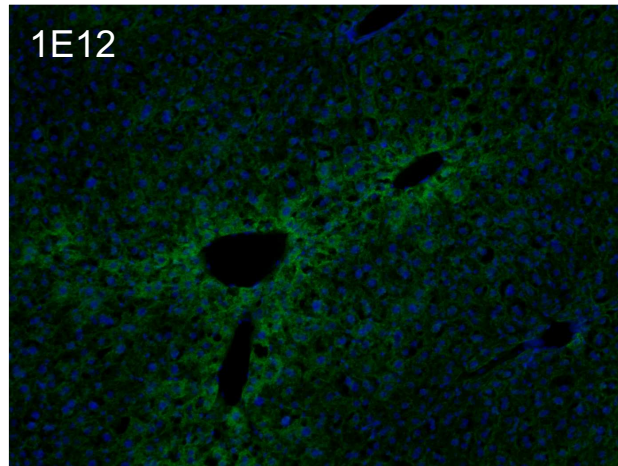


Richards, et al. Table 1: Molecular Analyses of Gene Therapy Treated *Pah* ^{Δ exon1/ Δ exon1} and *Pah*^{enu2/enu2} Mice

Gene Therapy	Blood Phe Pre-GT (μ M)	Blood Phe Post- GT (μ M)	Blood Tyr Pre-GT (μ M)	Blood Tyr Post-GT (μ M)	Brain Phe Post-GT (μ M)	Brain Tyr Post-GT (μ M)	Liver PAH activity (%WT)	Vg copy/liver diploid genome
<i>Pah</i> ^{Δexon1/Δexon1} mice								
1E12 AAV2/8 LSPmPAHfs female	2193	1928	38	37	1222	116	0.2%	1.0
1E10 AAV2/8 LSPmPAH male	3095	235	48	117	325	161	4.8%	2.9
1E11 AAV2/8 LSPmPAH female	2677	195	45	115	135	135	42%	16.2
1E12 AAV2/8 LSPmPAH male	1835	127	56	132	382	160	96.1%	50
<i>Pah</i> ^{enu2/enu2} mice								
1E11 AAV2/8 LSPmPAH 3 male/3 female	1983 \pm 540 ^a	176 \pm 52 ^a	ND	ND	ND	ND	7.7 \pm 2.2% ^a	8-42 ^b
1E12 AAV2/8 LSPmPAH 3 male/3 female	1921 \pm 603 ^a	99 \pm 22 ^a	ND	ND	ND	ND	14.8 \pm 3.3% ^a	56-291 ^b

ND – not done. ^a – mean \pm SD. ^b - range

Richards et al. Figure 4: Liver PAH Fluorescent Immunohistochemistry of Gene Therapy Treated *Pah* ^{Δ exon1/ Δ exon1} Mice



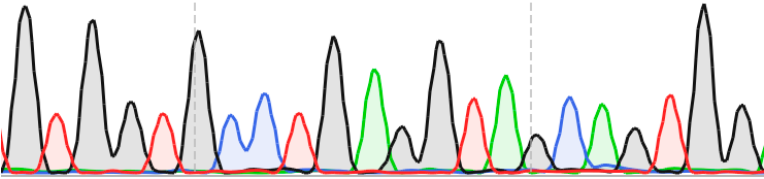
Richards et al. Supplemental Figure 1: sgRNA Off-Target Sanger Sequencing

A. Guide 4 Off-Target Sanger Sequencing

Guide 4 Sequence: GTGTTGCCCTGACGTAGCAGTGG

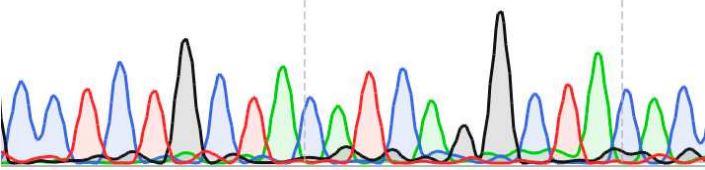
Location: Chr8:115751069
Sequence: GTGGTGCCTGAGGTAGCAGTGG
COSMID Score: 2.01

G T G G T G C C T G A G G T A G C A G T G G



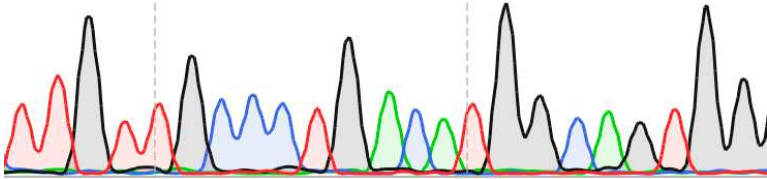
Location: ChrX:57746102
Sequence: GTGTAGCCTGATGTAGCAGAGG
COSMID Score: 2.03
Chromatogram displaying complementary sequence:

C C T C T G C T A C A T C A G G C T A C A C



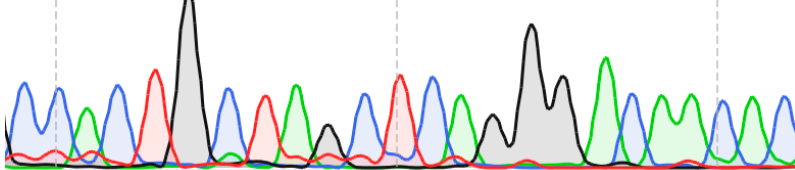
Location: Chr2:33139660
Sequence: TTGTTGCCCTGACATGGCAGTGG
COSMID Score: 3.72

T T G T T G C C C T G A C A T G G C A G T G G



Location: Chr8:86472947
Sequence: GTGTTGTCCCTGAGCTAGCAGTGG
COSMID Score: 3.72
Chromatogram displaying complementary sequence:

C C A C T G C T A G C T C A G G G A C A A C A C

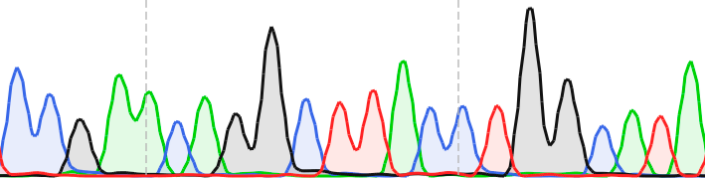


B. Guide 8 Off-Target Sanger Sequencing

Guide 8 Sequence: TTTGGGCAGGTAAGCCTGTTGGG

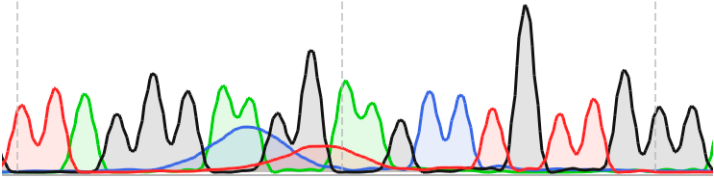
Location: Chr13:35827032
Sequence: TATGCCAGGTAAGCCTGTTGGG
COSMID Score: 1.02
Chromatogram displaying complementary sequence:

C C G A A C A G G C T T A C C T G G C A T A



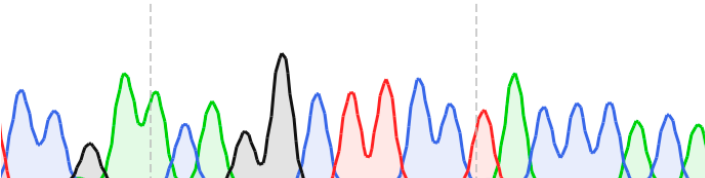
Location: Chr12:95441363
Sequence: TTAGGGAAGGAAGCCTGTTGGG
COSMID Score: 1.59

T T A G G G A A G G A A G C C T G T T G G G



Location: Chr1:22629912
Sequence: TGTGGGTAGGAAGCCTGTTGGG
COSMID Score: 1.57
Chromatogram displaying complementary sequence:

C C G A A C A G G C T T C C T A C C C A C A



Location: Chr5:110339511
Sequence: TCTGGTCAGGTAAAGCCTGTTGGG
COSMID Score: 1.84
Chromatogram displaying complementary sequence:

C C C A A C A G G C T T T A C C T G A C A G A

